

Eternal 5D data storage by ultrafast laser writing in glass

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ABSTRACT

Securely storing large amounts of information over relatively short timescales of 100 years, comparable to the span of the human memory, is a challenging problem. Conventional optical data storage technology used in CDs and DVDs has reached capacities of hundreds of gigabits per square inch, but its lifetime is limited to a decade. DNA based data storage can hold hundreds of terabytes per gram, but the durability is limited. The major challenge is the lack of appropriate combination of storage technology and medium possessing the advantages of both high capacity and long lifetime. The recording and retrieval of the digital data with a nearly unlimited lifetime was implemented by femtosecond laser nanostructuring of fused quartz. The storage allows unprecedented properties including hundreds of terabytes per disc data capacity, thermal stability up to 1000 °C, and virtually unlimited lifetime at room temperature opening a new era of eternal data archiving.

Keywords: form birefringence, ultrafast phenomena, material processing, optical data multiplexing.

INTRODUCTION

1.1 Importance of optical data storage

The evolution of information storage during the history of mankind involves four distinct eras: painted information, carved information, scripted information and digitalized information.^{1,2} The modern binary number system was first introduced by Gottfried Leibniz in 1703, who was inspired by a Chinese binary system called I Ching. The first modern breakthrough of digitization came in 1801 when the Jacquard loom was first demonstrated. The Jacquard loom simplified complex manufacturing textiles processes by controlling a chain of punched cards in a continuous sequence. The invention of this device enabled complex operations and data storage through paper punched cards. The first semiconductor diode in 1906 eventually allowed electronic circuit and data storage to become a reality.

Through the 20th century, one of the main innovations for data storage came about with the invention of optical discs (CDs, DVDs, Blu-rays). With high speed rotation drives (around 10,000 rpm), the writing rate of a Blu-ray disc could achieve around 100 MB/s. This development provided the ability to store large quantities of data in a weightless (around 20 g), small (standard 12 cm diameter) and high capacity (up to 1 TB) DVD or Blu-ray disc. With the invention of the laser diode (a gallium arsenide semiconductor diode firstly demonstrated in 1962) made it possible to compress the whole optical disc reading and writing system in a very compact form. As a result, the CD, DVD and Blu-ray read/write technology are ubiquitous in everyday life: laptops, video game consoles, cars, portable CD players, etc.

In the 21st century, the ability to store and access data is growing rapidly with the internet bringing all forms of information technology to everyone's fingertips. We cannot deny that this tangibility of information has made life faster, informative and more enjoyable than ever. However with this ability, every individual or company that is generating large amounts of data on a daily basis, which in turn introduces the desperate need of more efficient forms of data storage. The International Data Corporation investigated that total capacity of data stored is increasing by around 60% each year.³ As a result, more than 39,000 exabytes of data will be generated by 2020.⁴ This amount of data will cause a series of problems and one of the main will be power consumption. 1.5% of the total US electricity consumption in 2010 was given to the data centres in the U.S.² According to a report by the Natural Resources Defence Council, the power consumption of all data centres in the U.S. will reach roughly 140 billion kilowatt-hours per each year by 2020.⁵ This amount of electricity is equivalent to that generated by roughly thirteen Heysham 2 nuclear power stations (one of the biggest stations in UK, net 1240 MWe).

Most of these data centres are built based on hard-disk drive (HDD), with only a few designed on optical discs. HDD is the most popular solution for digital data storage according to the International Data Corporation.² However, HDD is not an energy efficient option for data archiving; the loading energy consumption is around 0.04 W/GB.⁶ In addition, HDD is an unsatisfactory candidate for long-term storage due to the short lifetime of the hardware and requires transferring

data every two years to avoid any loss. Therefore, the techniques which exhibit high capacity, low energy consumption and long lifetimes are essential for the future. Recent attempts to develop long-term and high capacity data storage and to prove that the data will survive for millions to billions years have been promising.⁷ However, despite the space eternal memory concepts, the proposed alternative technologies storing information on DNA,⁸ silicon-nitride/tungsten based medium,⁹ microscopically etched/electroformed nickel plates^{10,11} are technologically expensive and slow to be practical.

The current solution is the optical disc technique, which only holds a small percentage of data centres usage at present. Due to the fact that data cannot be reached instantaneously, optical disc is not the best option for major storage. Nevertheless, since energy is mainly consumed during the initial data writing process, optical discs is more economic in energy usage. The optical disc drive will stay idle after the data is well written. Hence, the advantages such as low price and reduced energy consumption makes the optical disc system the ideal system for data archiving and internet backup currently. It enables the storage of thousands of optical discs and read/write, transfer and placement of the discs simultaneously. The specific disc, which contains data from any one user, will be picked up and transferred to the read/write drive before accessing based on user habits. This kind of optical-disc-based data storage system can lower the cost and spend less energy, meanwhile ensuring that users can access files from their own terminals instantly.

We believe that optical data storage, well known for its green characteristics, will be the mainstream technique for data archiving in the near future. The main kind of optical discs employed for data archiving in big data centres are Blu-ray discs, which are limited to tens of GBs. However, can the GB-scale Blu-ray disc cope with the explosive demand of data storage? In 2020, tons of Blu-ray discs will occupy tremendous amounts space (about 34 round trips to the moon with Blu-ray discs).⁴ Therefore, an optical disc which enables high capacity is essential for our future needs. Currently optical data storage is based in predominantly planar technology, which exploits the linear light absorption of the material, thus is constrained to the surface modification. In addition, planar technology is limited in the number of modification layers, consequently restricting the capacity. In order to further expand the potential optical data storage capacity, a volumetric approach was suggested, known as 3D optical memory, where data can be stored in multiple layers making use of the whole volume of the material.

1.2 Breaking the storage-capacity limit by multiplexing

Securely storing large amounts of information over even relatively short timescales of 100 years, comparable to the human brain lifetime, is a challenging problem.^{12,13} A general rule of thumb, defined in particular by the diffusion process, is as storage density increases, the lifetime of said storage will decrease. For example, vast amounts of data written by individual atoms can only be stored for 10 ps at room temperature.^{14,15} The conventional optical data storage technology used for CDs and DVDs has reached capacities of hundreds of gigabits per square inch, but its lifetime is limited to several decades.^{16–18} The major challenge is the lack of appropriate storage technology and medium possessing the advantages of both high capacity and long lifetime. Unlike CD, DVD and Blu-ray discs, which need to add the extra layers physically, the three dimensional (3D) optical storage technique can write potentially thousands of layers (Figure 1 (a)).¹⁹ Latest developments in 3D optical memory has achieved an approximate capacity of 10 TB in a small spot size of 100 nm by utilizing a dual beam technique named super-resolution photoinduction-inhibition nanolithography (SPIN).²⁰ This technology provides the possibility of breaking the diffraction barrier and achieving the smallest features at sizes down to 9 nm.²¹

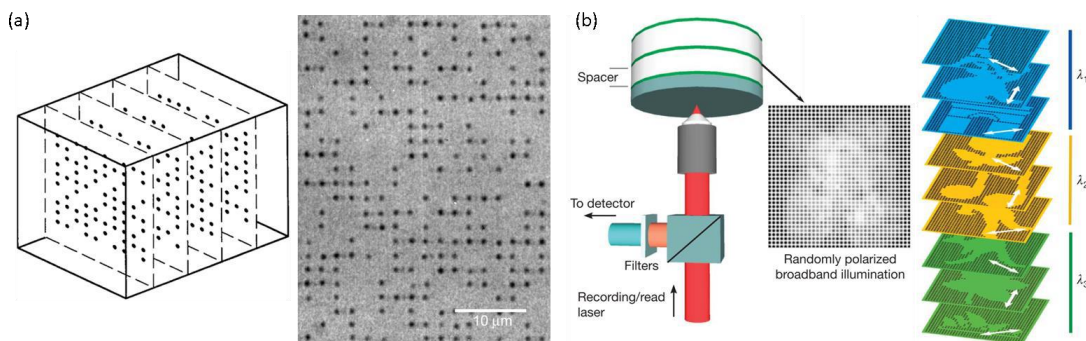


Figure 1. (a) Binary 3D data pattern stored in fused silica by femtosecond laser.¹⁹ (b) Multiplexed 5D optical memory using gold nanorods. The patterns were fabricated using different wavelengths and polarization states as 4th and 5th dimensions.²²

Normally in a single memory cell or voxel, only 1 bit of data can be stored. However, there is the potential of storing more than one bit in a single voxel by implementing multiplex technology. As a result, the total storage capacity can be

further increased alongside readout speed. This approach can be applied in materials which exhibit sensitivity to not only the intensity of the light source used to read but also to other properties of light. The signal can then be read in several independent channels, thus enabling multiplexing of data. Several parameters like polarization,^{22–25} wavelength,^{22,26} space,^{19,20,27,28} fluorescence^{27,28} have all been deliberated as the additional dimensions for optical data storage. Various materials have been implemented for multi-dimensional data storage such as silver clusters embedded in glass²⁸ and gold (Figure 1 (b)) or silver nanoparticles.^{22,29} The method of data multiplexing is an alternative to holographic data storage,³⁰ which overcomes the capacity limit dictated by optical diffraction. Optical recording based on femtosecond laser writing exhibits two advantages due to its ability in high-precision and high-energy deposition. It was first proposed and demonstrated in photopolymers,³¹ later in the bulk of non-photosensitive glass.^{19,32,33} More recently polarization multiplexed writing was demonstrated by using self-assembled nanogratings produced by ultrafast laser writing in semiconductor thin-films³⁴ or fused quartz.^{35–38} The nanogratings, featuring 20 nm embedded structures (Figure 2), the smallest ever produced by light.^{39–44} Despite several attempts to explain the physics of the peculiar self-organization process, the formation of these nanostructures still remains debatable.^{37,40,44} On the macroscopic scale, the self-assembled nanostructure behaves as a uniaxial optical crystal with negative birefringence. The optical anisotropy, which results from the alignment of the nanogratings, referred to as form birefringence, is of the same order of magnitude as positive birefringence in crystalline quartz.^{45,46}

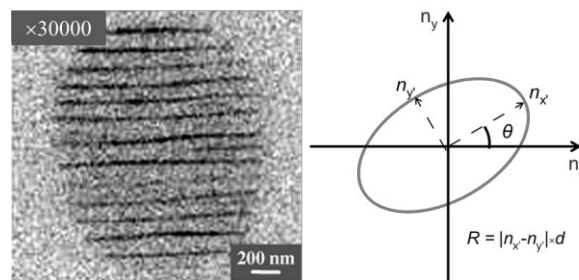


Figure 2. Secondary electron image of femtosecond laser induced nanogratings in silica glass with the schematic diagram of its slow axis angle (θ) and retardance value (R), where n_x , n_y are refractive indices corresponding to slow and fast axis, and d is the thickness of induced structure.

The two independent parameters describing birefringence, the slow axis orientation (4th dimension) and strength of retardance (5th dimension, defined as a product of the birefringence and length of structure) (Figure 3), were explored for the optical encoding of information in addition to three spatial coordinates.^{34,35,37} The slow axis orientation and the retardance are independently manipulated by the polarization and intensity of the incident beam. As a result, the polarization and intensity multiplexing increases the amount of data held per modification spot. Simultaneously the reading speed is increased since more number of bits can be retrieved by reading one modification spot compared to conventional data storage where each physical spot contains only one bit.

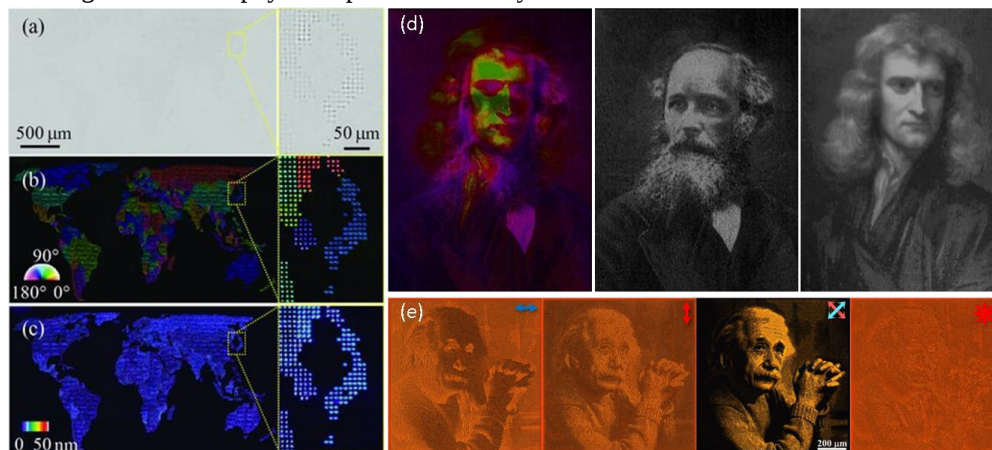


Figure 3. Images demonstrating multi-dimensional optical printing. “Small World Map” (a) optical transmission image of the laser-induced nanogratings with its space-variant (b) slow axis orientation and (c) induced phase retardation.³⁷ (d) Images, from left to right, representing in false colours the recorded information in slow axis and retardance, and decoupled portraits of Maxwell and Newton.³⁵ (e) Einstein’s portrait imprinted in amorphous silicon thin-films. Arrows indicate the polarization states used for extracting the image.³⁴

1.3 Rewriting and durability of structures in glass

Besides the benefits of multiplexing, the 5D optical data based on nanogratings can be also erased and rewritten, which are two important features when considering data storage. The initial nanogratings can be replaced with new ones whose direction is dependent on the incident rewrite laser beam.⁴⁷ The rewriting process can be clearly observed in Figure 4 (a-d), where the original spot is rewritten with 3, 30, 300 and 4000 pulses of a beam with a laser polarization rotated by 45°. 200 pulses should be enough to erase the previous induced birefringence signal while not generating a strong new signal from the rewrite laser pulses (Figure 4. 4 (e)). About 2000 pulses could completely rewrite the structure, which has the same birefringence signal as the original one.

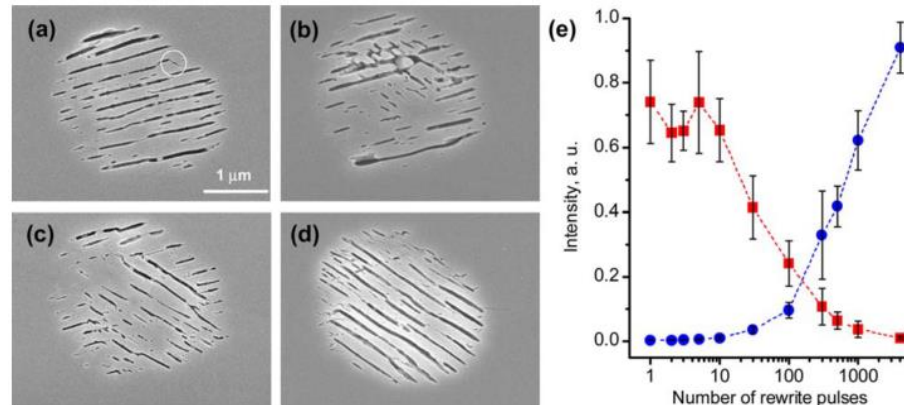


Figure 4. Rewriting laser-induced nanogratings with (a) 3, (b) 30, (c) 300 and (d) 4000 pulses. The rewrite polarization is at 45° to the original polarization. (e) Intensity of the birefringence signal as a function of number of rewrite laser pulses where the input polarization is at 45° to the original nanogratings (red squares), and at 45° to the replacement nanogratings (blue dots).⁴⁷

The 5D optical storage technique applied to fused silica is ideal due to fused silica's high chemical and thermal stability (Figure 5), making fused silica the ideal medium for long term data storage.⁴⁶ Latest studies have demonstrated a fused silica based long lifetime 3D optical memory that has a data capacity equivalent to a DVD disc.^{48,49} Additional evaluation results indicate that this optical memory possesses a lifetime of over 319 million years.⁴⁸

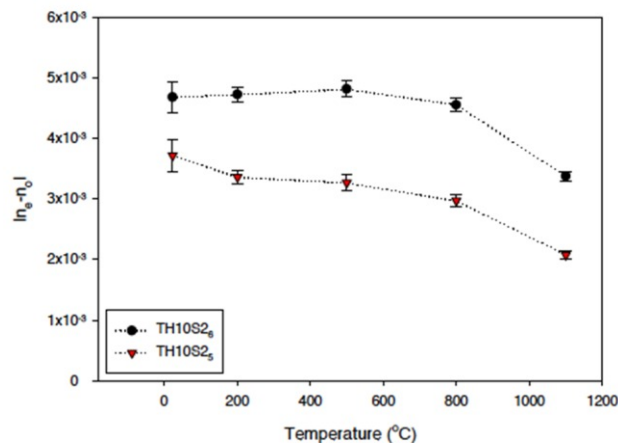


Figure 5. Laser induced birefringence value in fused silica as a function of annealing temperature. Pulse energy was set to 1.60 μJ (black dots) and 2.14 μJ (red triangles).⁴⁶

The situation for 5D optical memory is even superior. Previous studies indicate that the phase retardance only starts to drop at 800°C, but the difference of the phase retardance generated by two levels of energy remains almost the same.⁴⁶ This behaviour is beneficial for the memory application. Even if the birefringence signal drops after a certain period of time or under some special conditions, the data will still be readable as long as the difference between each signal level is sufficient.

ETERNAL 5D DATA STORAGE BY ULTRAFAST LASER WRITING IN GLASS

1.4 Data recording

Data recording experiments were performed with an Yb:KGW based femtosecond laser system (Pharos, Light Conversion Ltd.) operating at 1030 nm and delivering 6.3 μJ pulses at 200 kHz repetition rate and pulse duration tunable from 270 fs to 800 fs. Even though longer pulse duration can induce higher retardance (80 nm),⁵⁰ it also leads to higher stress accumulation and eventual material cracking.¹⁹ As a result, the pulse duration was set to 280 fs. Three modification layers were inscribed with a femtosecond laser 130-170 μm below the surface of a fused quartz (SiO_2 glass) sample by a 1.2 NA ($\times 60$) water immersion objective.

In the recording procedure, groups of birefringent dots were simultaneously imprinted at the designated depth (Figure 6). Each group, containing from 1 to 100 dots, was generated with a liquid crystal based spatial light modulator (SLM) and 4f optical system. The holograms for the SLM were generated with an adapted weighted Gerchberg-Saxton (GSW) algorithm, which enabled discretized multi-level intensity control.⁵¹ The discretized multi-level intensity control enabled data multiplexing via retardance. By using the adapted GSW algorithm, several discrete levels of intensity could be achieved with a single hologram.⁵¹ However, the algorithm controls only the relative ratio of different intensity levels. As the number of dots varies from one hologram to another, the absolute intensity of each spot varies. Thus, the corresponding intensity levels generated by different holograms are different and create fluctuations of the retardance value from one hologram to another. The problem is resolved by introducing a negative feedback loop into the algorithm, which redistributes the surplus of energy out of the modification region, fixing each intensity level generated by all holograms to the certain value. The excess energy is blocked by an aperture (AP) placed after the half-wave plate matrix (HPM) and does not affect data recording.

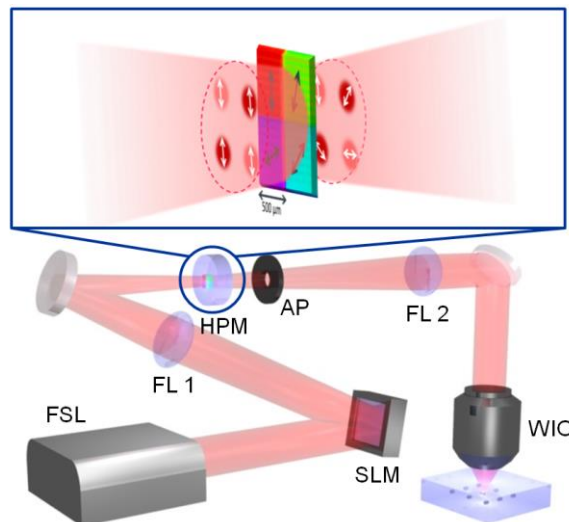


Figure 6. 5D optical storage ultrafast writing setup. FSL and FL represent femtosecond laser and Fourier lens, respectively. SLM and HPM represent spatial light modulator and half-wave plate matrix. AP and WIO are the aperture and water immersion objective (1.2 NA). Linearly polarized (white arrows) light with different intensity levels propagate simultaneously through each half-wave plate segment with different slow axis orientation (black arrows). The colours of the beams indicate different intensity levels.

The oriented slow axis is perpendicularly to the polarization of the incident beam. Hence, the azimuth of the slow axis can be controlled by the polarization of the incident beam, which is normally accomplished by rotating a half-wave plate. However, the rotation takes a relatively long time (>10 ms) and considerably reduces writing speed. To avoid this, a laser imprinted half-wave plate matrix (see HPM in Figure 6, made of 4 segments) was added to the 4f optical system enabling motion free polarization control. In the focus plane of the first Fourier lens, where the half-wave plate matrix was placed, several beams with different intensity distributions were projected by the hologram displayed on the SLM. After passing through the segments of the half-wave plate matrix, beams with different polarizations were obtained. Subsequently, the plane of the half-wave plate matrix that contains predefined intensity and polarization distribution is reimaged directly into the sample by the microscope objective. After synchronizing the movement of the sample with the refresh rate of the SLM, multiple birefringent dots with four slow axis orientations and various phase retardance levels

can be simultaneously imprinted (Figure 7). The information was encoded into two states of retardance and four states of slow axis orientation. Thus, each birefringent dot contained 3 bits of information.

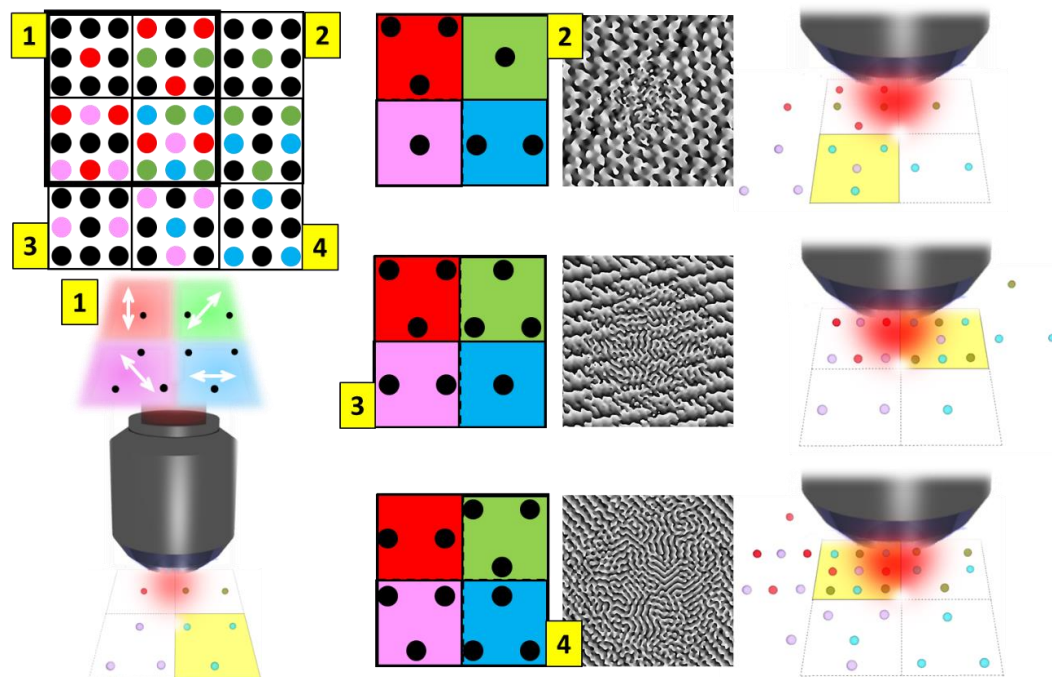


Figure 7. The schematic illustration of data storage by the femtosecond laser direct writing technique. The digital data is encoded in spatially variant polarization states of modification spots and divided into the regions whose size is defined by the number of spots and its density. The half-wave plate designed of four sub-regions with different orientations of optical axis (red, green, violet and blue) is fabricated and placed before the objective lens. Changing the computer generated holograms, the multi-beam patterns are formed and specific sub-regions of the wave plate are illuminated. Simultaneously controlling the spatial position of the substrate, the target distribution of spots is written in glass. Black spots indicate the original polarization state of the beam. Numbers indicate the specific region of the spots matrix.

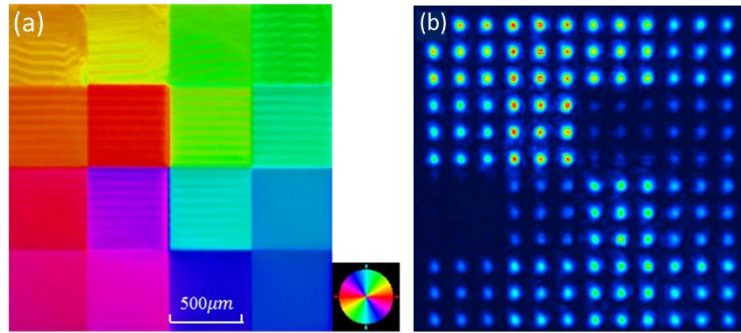


Figure 8. (a) Color-coded slow axis orientation of half-wave plate matrix imprinted in silica glass. (b) Intensity profile of the linearly polarized light transmitted through the wave plate matrix and linear polarizer.

1.5 Readout results and optimization

The readout of the recorded information encoded in nanostructured glass was performed with a quantitative birefringence measurement system (Abrio, CRI Inc.) integrated into an optical microscope (BX51, Olympus Inc.). Light from a halogen lamp was circularly polarized and filtered with a bandpass filter at 546 nm. After being transmitted through the layers containing information, the signal was collected with a 0.6 NA objective and the state of polarization was characterized with a universal liquid crystal analyzer.

Typical values of the retardance measured in the experiments was 40 nm. Using this system, three birefringent layers separated by 20 μm in depth could be easily resolved (Figure 9 (a), (b)). The phase retardance (Figure 9 (c)) and slow axis orientation (Figure 9 (d)) was extracted from the raw data, then normalized (Figure 9 (e) and (f)) and discretized before the final result was achieved (Figure 9 (g) and (h)).

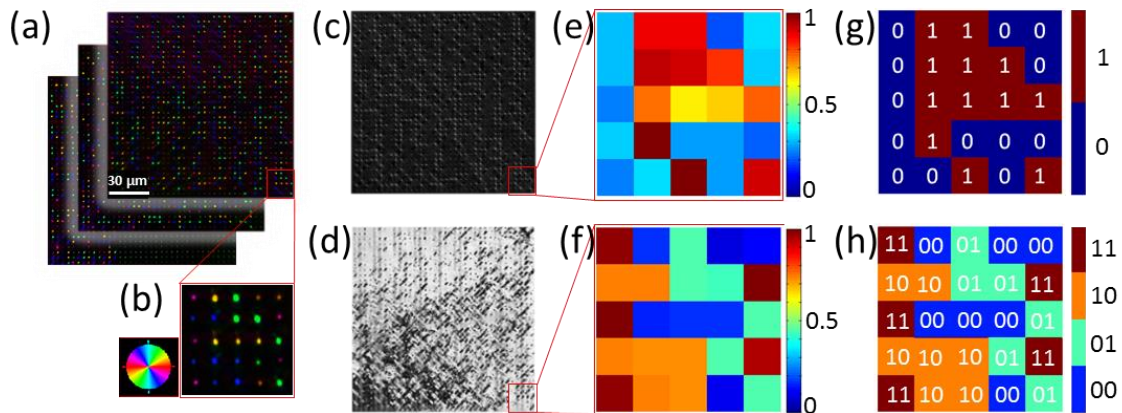


Figure 9. 5D optical storage readout. (a) Birefringence measurement of the data record in three separate layers. (b) Enlarged 5×5 dots array. Pseudo colour indicated the orientation of slow axis. (c) Retardance distribution retrieved from the top data layer. (d) Slow axis distribution retrieved from the top data layer. Enlarged normalized (e) retardance and (f) slow axis matrices with its corresponding (g), (h) retrieved binary data.

The information was decoded by combining two binary data sets retrieved from the phase retardance and the slow axis orientation. Out of 11664 bits, which were recorded in three layers, only 42 bits errors were obtained (Figure 10). Most of the errors were recurring and can be removed by additional calibration procedures, which accounts for the retardance dependence on polarization.

In the 5D optical storage readout shown in Figure 9 (a)), the distance between two adjacent spots was 3.7 μm and the distance between each layer was 20 μm. Applying the same writing method on a disc of conventional CD size with 60 layers, 18 GB capacity can be achieved. Using the same parameters it was also successfully recorded across three layers a digital copy of a 310 KB file in PDF format.³⁸ Furthermore, it was noticed that some of the errors are shown frequently in the retrieved text. The retardance value of spots induced by different polarizations but same intensity depends on the

slow axis orientations resulting in repeated errors in Figure 10. This polarization dependence effect could be related to the pulse front tilt of ultrashort light pulses.^{37,52,53}

The idea of the optical memory based on femtosecond laser writing in the bulk of transparent material was first proposed in 1996. More recently ultrafast laser writing of self-assembled nanogratings in glass was proposed for the polarization multiplexed optical memory, where the information encoding would be realized by means of two birefringence parameters, i.e. the slow axis orientation (4th dimension) and strength of retardance (5th dimension), in addition to three spatial coordinates. The slow axis orientation and the retardance can be controlled by polarization and intensity of the incident beam respectively. The unprecedented parameters including 360 TB/disc data capacity, thermal stability 5p to 1000°C and practically unlimited lifetime. However the implementation of digital data storage, which is a crucial step towards the real world applications, has not been demonstrated by ultrafast laser writing. Here we successfully recorded and retrieved a digital copy of the text file in 5D using polarization controlled self-assembled ultrafast laser nanostructuring in silica glass.

Figure 10. Retrieved text from 5D optical data. The letters with errors were bolded.

A series of dots were imprinted in fused silica by 400 laser pulses with 16 different polarizations and two levels of energy (Figure 11). The energies were set to 50 nJ and 75 nJ. The distribution of retardance values induced by different polarizations follow a sinusoidal dependence. In order to optimize the readout process, additional calibration has to be implemented. In this case, the predefined retardance reference value must be set differently according to the slow axis orientations.

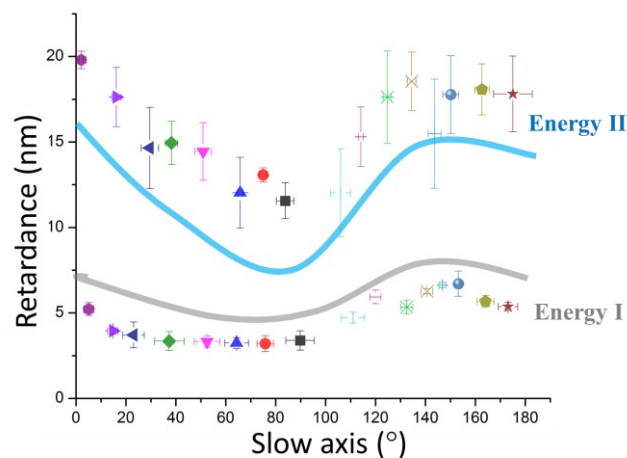


Figure 11. Retardance dependence on 16 different slow axis orientations written by (a) 400 pulses with pulse energies of 50 nJ (Energy I) and 75 nJ (Energy II) at 200 kHz repetition rate.

A paragraph from Encyclopedia Britannica about Sir Isaac Newton was recorded in silica glass. There were four modification layers, separated by 5 μm . In order to reduce the crosstalk between layers, generate less stress and increase the optical storage capacity, the dots were arranged similarly to a body-centred cubic geometry (Figure 12 (a)). When the birefringence measurement microscope was used to focus on the specific layer, the other layers were out of focus and did not affect the measurement values. This arrangement scheme increases the capacity four times in comparison to the one with 20 μm layer separation.

There were 1087 Bytes of data being recorded in four modification layers. The first word in this recorded Encyclopaedia Britannica paragraph is illustrated indicating how the optimization influenced the final readout results (12 (b)). By using the readout method modified according to the experimental results, the error rate was reduced to 0.22% (19 out of 8696 bits) compared to 0.36% previously.

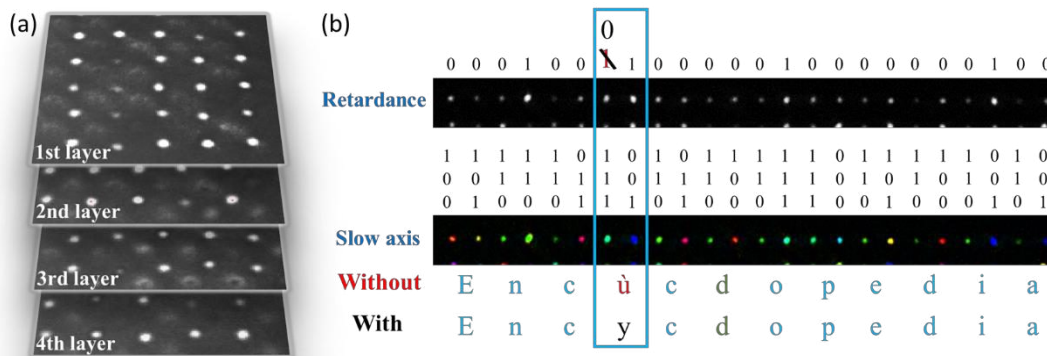


Figure 12. (a) Four layers of laser-induced birefringent spots distributed in a body-centred cubic lattice. Measured retardance value is normalized to maximum. (b) Readout the data without and with optimization, where the retardance reference value is set differently according to the slow axis orientations.

Many commercialized birefringence measurement systems require electrically controlled retarders and several intensity images to retrieve the birefringence distribution. Therefore, it is not suitable for memory readout systems where a high sampling rate is essential. To overcome this problem, the real-time birefringence measurement system proposed by T. Onuma and Y. Otani can be employed.⁵⁴ The core device in the system is a matrix of four linear polarizers as analysers with their optical axes oriented at 0°, 45°, 90° and 135°. Similar to a Bayer mask used in colour-sensitive camera with four independent colour filters assembled into one pixel, the matrix operates as a linear polarizer with four separate orientations. In addition, by applying the technology based on ultrafast laser nanostructuring, the analysers of tens of micrometres size with different orientations were fabricated.⁵⁵ The half-wave plates oriented at 0°, 22.5°, 45°, 67.5° and a linear polarizer are equivalent to the four linear polarizers as required. Each polarizer matches each pixel of the CCD matrix one by one (Figure 13).

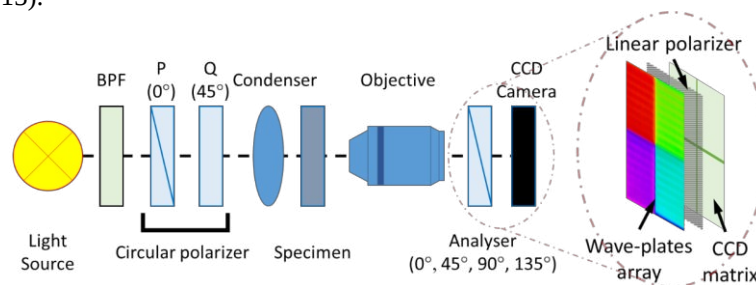
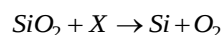


Figure 13. Schematic drawing of fast birefringence measurement system: band-pass filter for 546 nm (BPF), linear polarizer (P), quarter-wave plate (Q), condenser, objective lens, half-wave plates array, linear polarizer and CCD camera. The colours of the wave plates array indicate different optical axis orientation.

1.6 Lifetime of nanostructured glass

The femtosecond laser induced nanogratings comprise of periodic assembly of nanoplanes with 20 nm thickness separated by about 300 nm. Close investigation reveals that refractive index of nanoplanes is reduced due to material porosity.⁴⁴ The formation of porous regions consisting of nanovoids filled with oxygen could be explained by the following mechanism: femtosecond irradiation of silica glass produces self-trapped excitons with a lifetime of several microseconds. Recombination of self-trapped excitons is accompanied by generation of molecular oxygen due to the photosynthesis-like reaction,



where X denotes an exciton. The nanovoids could collapse with time leading to disappearance of the form birefringence of the modified region. Previous annealing experiments indicated that such modification can withstand at least 2 hours of thermal annealing at 1000°C.⁴⁶ However the accelerated aging measurements are required to evaluate the stability of nanogratings at room temperature and estimate the activation energy of nanovoids collapse. The thermally activated decay time τ at the certain temperature T can be evaluated by Arrhenius law:

$$\frac{1}{\tau} = k = A \times \exp\left(-\frac{E_a}{k_B T}\right)$$

where k – decay rate, E_a – the activation energy, A – the frequency factor, T – the absolute temperature and k_B – the Boltzmann constant.

The decay rate was evaluated at several annealing temperatures in the range from 1173 K to 1373 K, where measurable retardance change could be observed, by measuring the relative retardance decrease versus the annealing time (Figure 14 inset). The experiment was performed with four different laser writing energies (0.75 – 1.5 μJ). The variation of the relative retardance decrease for different energies were within 5%. The birefringent structures (uniform squares 0.5×0.5 mm) used for these measurements were written with the same laser setup as described above. A relatively large area of the written structures was chosen to increase the precision and repeatability of retardance change measurements. From the obtained information, decay times at certain temperatures were evaluated and placed on the Arrhenius plot. The decay time at lower temperatures was easily extrapolated by a linear fit (Figure 14). The best linear fit was obtained with activation energy of 1.81 ± 0.07 eV (thermal energy at room temperature is about 26 meV) and the frequency factor of 135 Hz. For comparison the activation energy measured in the erasure of the type I fiber Bragg gratings was 0.79 – 2.04 eV depending on the sample composition.⁵⁶ Assuming the scaling in Figure 14 holds at room temperature (303 K) the decay time of nanogratings is $3 \cdot 10^{20 \pm 1}$ years, indicating unprecedentedly high stability of nanostructures imprinted in fused quartz. Even at elevated temperatures of $T = 462$ K, the extrapolated decay time is comparable with the age of the Universe – 13.8 billion years. Obviously extrapolation over such a long lifetime is not absolutely correct due to increasing error. Also it neglects the temperature variation over long period of time, which cannot be easily evaluated. On the other hand it is clear that if the temperature does not increase drastically, we would have an optical data storage with seemingly unlimited lifetime.

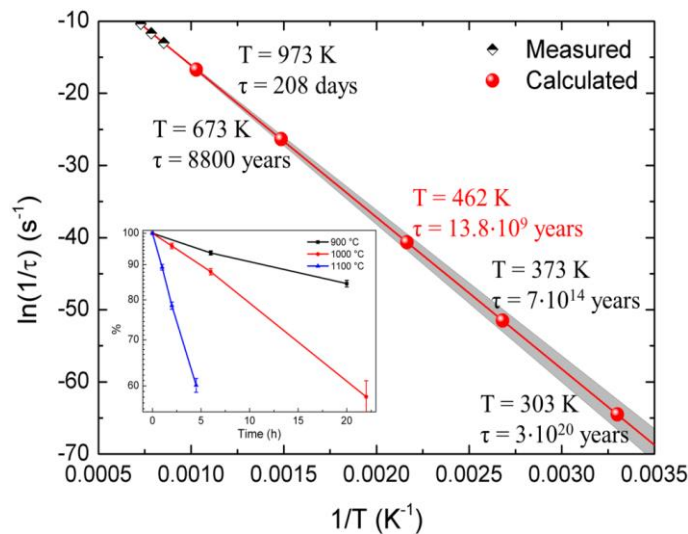


Figure 14. Arrhenius plot of nanogratings decay rate. Black symbols indicate measured values; red symbols are calculated based on fitting results. The grey shaded zone indicates the tolerance of extrapolated values. At the temperature $T = 462$ K nanogratings would last for the current life time of the Universe. (Inset) The decay of the strength of retardance with time at different annealing temperatures.

The overall data storage techniques can be separated into three most-common groups: semiconductor, magnetic and optical. Semiconductor data storage such as flash drives and solid-state drives (SSD) provide a lifespan around ten years.⁵⁷ This is due to the floating-gate transistors in semiconductor based memory becoming unreliable after a number of program/erase cycles.⁵⁸ Hence, the lifetime of this memory is mostly dependent on its workload, e.g. SSD memory with heavy workload (320 GB/day) only has 10% of lifetime as compared to the memory with less of a workload (32 GB/day).⁵⁹

For magnetization-based memory, such as HDD, needs to transfer data every couple of years in order to prevent data loss, while the data stored in conventional optical discs such as CD, DVD, HD DVD and Blu-ray only last tens of years. However, already commercialized Millenniata optical discs (M-DISC™) claimed that their discs have an extra-long lifetime of up to a 1000 years.⁶⁰ Also, void-based optical memory in fused silica indicate a lifetime of 300 million

years.^{49,61} Other schemes such as holographic memory and phase change memory can only reach the lifetime of a few decades.^{62,63} Data storage approaches are compared in Figure 15 in order to give a more intuitive view of storage lifetimes.

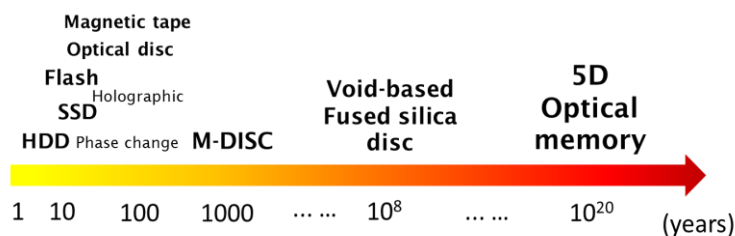


Figure 15. Schematic illustrations of typical lifetimes of different data storage approaches.

5D optical memory with its nearly unlimited lifetime is superior to other memory solutions. Additional guides stored as visual information could be easily used as a key for the further decoding processes. The complex recording/readout of the eternal 5D optical data storage in silica glass: *Eternal Time Capsule* is demonstrated in Figure 16.

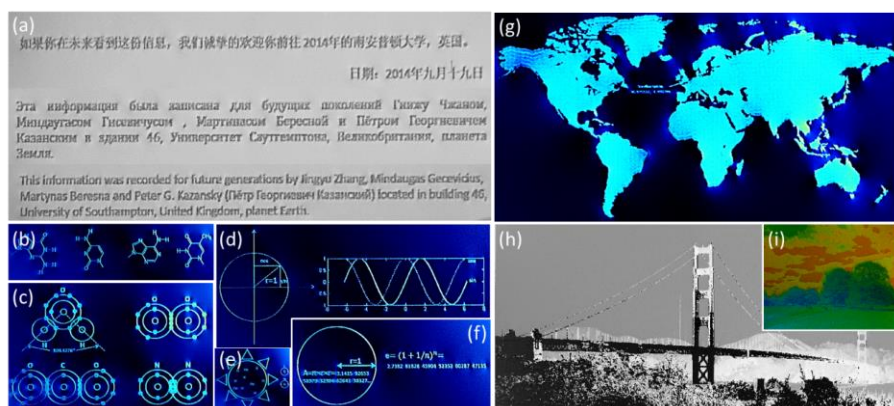


Figure 16. Eternal 5D optical data storage: (a) messages written in Chinese, Russian and English languages, (b) structure of four bases found in DNA, (c) molecular structures of water, oxygen, carbon dioxide and nitrogen, (d) profiles of $\sin$ and $\cos$ functions, (e) mechanism of star formation, (f) mathematical constants π and e , (g) world map with coordinates of Building 46 in Southampton University, and (h-i) sceneries on Earth.

CONCLUSIONS

The recording of a digital document into a highly stable memory is a vital process towards an eternal archiving. Although digital data storage techniques are capable of storing huge amounts of information, the lifetime is limited to decades. Recent progress in memory technologies allowed to encode the information that is capable of surviving for billions of years.⁷ The successful implementation of femtosecond laser nanostructured fused quartz as high-density and, assuming the scaling of Arrhenius plot holds, long-lifetime storage medium enabled the demonstration of eternal 5D optical memory. The storage allows hundreds of terabytes per disc data capacity, thermal stability up to 1000°C and nearly unlimited lifetime at room temperature. We believe that the eternal 5D optical data storage in glass can be produced on a commercial scale for organizations, such as national archives, museums, libraries or any private companies. Also, the projects such as “*Time Capsule to Mars*”,⁶⁴ “*Moon Mail*”,⁶⁵ or “*Lunar Mission One*”⁶⁶ could benefit from the extreme durability of data imprinted by femtosecond laser in quartz glass, which is essential for preserving comprehensive information and storing it in space for future generations. More futuristically, “text messaging to the future” could be now possible. Could the technology of the future be advanced enough to send the reply?

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